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Assessment of three types of heat pipe solar collectors

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ABSTRACT

New comparative tests on three different types of heat pipe solar collectors are presented in this paper. These three collectors are installed in parallel and tested at the same working conditions.

Results are also presented in terms of efficiency plotted against temperature of the heat transfer fluid entering the collector minus the ambient air divided by the global solar irradiance upon the aperture plane of the collector. This allows representing the comparative characteristics of the three collectors when operating under variable conditions, especially with wide range of incidence solar radiation.

Contents

1. Introduction

The solar collectors are the important component of any solar energy system.

They gather the solar, transform its radiation into heat, and then transfer that heat to a fluid. The use of solar energy for space heating, cooling, and supplying domestic hot water to buildings is receiving serious attention at present due to the mounting public awareness of the shortage of conventional fuels.

Several studies on heat pipe solar collectors of various geometries are reported in the literature. Riffat et al. [1,2] studied thermal performance of a thin membrane heat pipe solar collector and hybrid heat pipe solar collector/CHP system to provide electricity and heating for a building. Thermal behaviour of flat heat pipe solar collectors was studied by various researchers [3–7]. Hull [8] investigated heat transfer factors and thermal efficiency for heat pipe absorber array connected to a common manifold and predicted that array with less than 10 heat pipes have significantly less efficiency than a conventional flow-through collector. Several potential advantages are available with the employment of heat pipe solar collectors Bienert [9]. In heat pipes the position of condenser is not restricted to any specific orientation and it may be utilized in any orientation. Gravity-assisted heat pipes are unidirectional conductors – they behave as thermal diode. If they are properly oriented, heat is transferred only from the evaporator to the condenser but never in the reverse direction. This feature can cut off the heat loss when the absorber temperature is lower than that of the liquid in the heat exchanger. Also, since heat pipes are sealed, by selecting suitable working fluids, compatible with wick and pipe materials, corrosion can be minimized. Another advantage is redundancy, that is, a failure in one heat pipe would not have a major effect on the operation of the collector. Freezing can be eliminated through working fluid selection, and, therefore only the heat exchanger section must be insulated.

In the present study the condenser of the heat pipe is elevated so that the condensate returns to the evaporator with the assistance of

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Nomenclature

A_a	transparent frontal area (m^2)
A_g	gross collector area (m^2)
C_p	specific heat of the heat transfer fluid (J/(kg °C))
F_R	solar collector heat removal factor
G	solar irradiance (W/m^2)
m	mass flow rate of heat transfer fluid (kg/s)
Q_u	rate of useful energy extraction from the collector (W)
$T_{f,e}$	temperature of the heat transfer fluid leaving the collector (°C)
$T_{f,i}$	temperature of the heat transfer fluid entering the collector (°C)
U_L	solar collector heat transfer loss coefficient (W/m^2 °C)
η	collector efficiency (%)
α	absorptance of the collector absorber surface for solar radiation
τ	transmittance of the solar collector cover plate

gravity. When the heat pipe is operating in gravity-assisted mode, a high heat transfer capability can be achieved. Further, no wick is required in the condenser since gravity drains the condensate from the wall to the paddle. However, a wick structure is required for circumferential distribution of liquid in the evaporator. For further discussion in this paper, solar collectors with heat pipe each individual heat pipe mechanically bonded to the aluminium absorber plates with different condenser design referred to as collector Types I and II and in Type III the absorber the absorber constructed from continuous finned tube. In this paper three collectors simultaneously tested for thermal performance and it is important for the determination of accurate comparative performance data.

2. Heat pipe

Heat pipes are structures of very high thermal conductance. They permit the transport of heat with a temperature drop, which are several orders of magnitude smaller than for any solid conductor of the same size. Heat pipes consist of a sealed container with a small amount of a working fluid. The heat is transferred as latent heat energy by evaporating the working fluid in a heating zone and condensing the vapour in a cooling zone, the circulation is completed by return flow of the condensate to the heating zone through the capillary structure which lines the inner wall of the container [10,11]. Schematic diagram of the heat pipe is shown in Fig. 1. This paper deals with the study of the performance of flat plate solar collectors utilizing heat pipes.

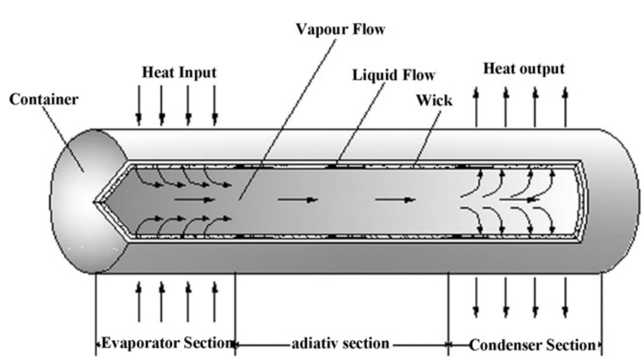

Fig. 1. Heat pipe.

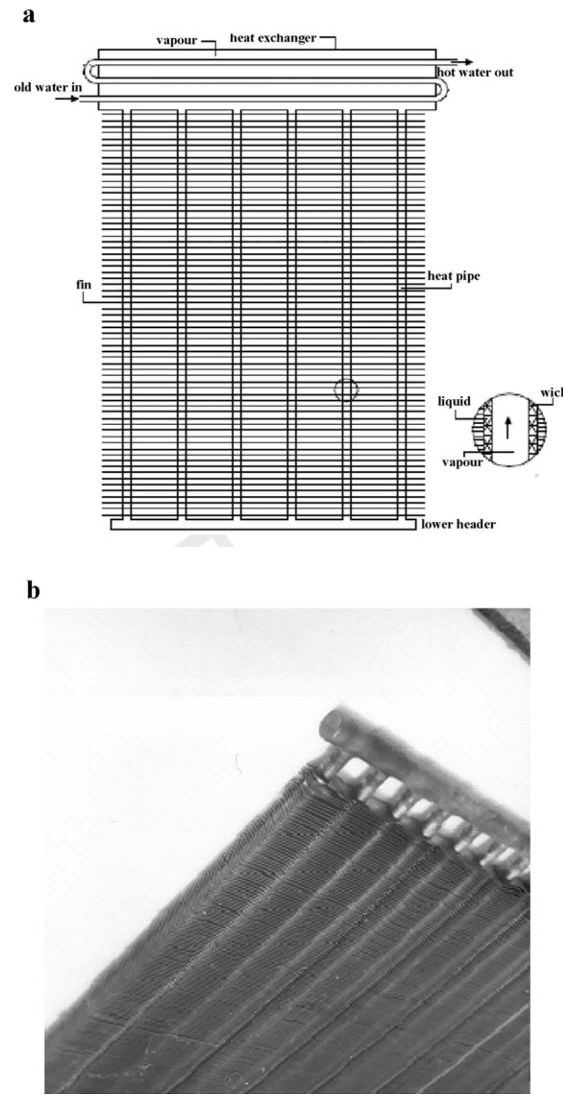

Fig. 2. Heat pipe solar collector Type I. (a) Heat pipe solar collector. (b) Constructed Heat pipe solar collector.

The heat pipe is characterized by:

- Very high effective thermal conductance.
- The ability to act as a thermal flux transformer.
- An isothermal surface of low thermal impedance.
- Thermal diode, heat is transferred only from the evaporator to the condenser, but never in the reverse direction.

3. Heat pipe solar collectors (HPSC)

All three heat pipe solar collectors are shown in Figs. 2–4 [12–14] consists of heat pipes with wick consisted of two layers of 100-mesh stainless steel screen fitted to the evaporator section. Each heat pipe tube was thoroughly cleaned with acetone followed by a rinse in demineralised water. After the tube had been vacuumed to 10^{-4} Torr, achieved with a rotary vacuum pump and a diffusion pump, a specified amount of working fluid (25 ml of ethanol) was charged into the tube. The tube was then prepared for crimping and final sealing. Fig. 5 shows the heat pipe filling rig. Ethanol filled heat pipes are more efficient and less susceptible to freezing. In Types I and II each individual heat pipe was mechanically bonded to the aluminium absorber plates at 160 mm pitch. In Type III the absorber the absorber constructed from continuous

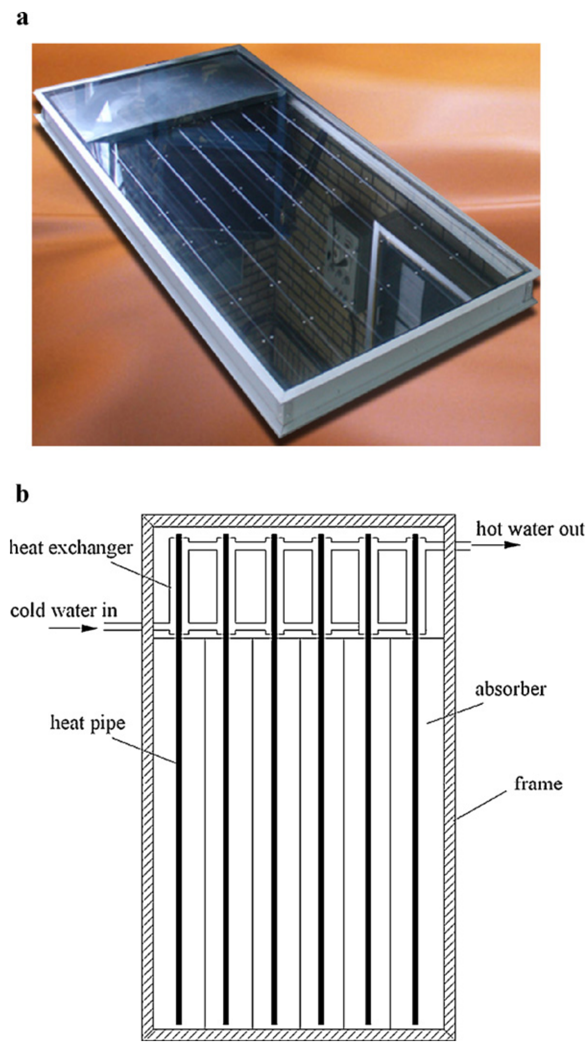

Fig. 3. Heat pipe solar collector Type II. (a) Constructed heat pipe solar collector. (b) Detail of heat pipe solar collector.

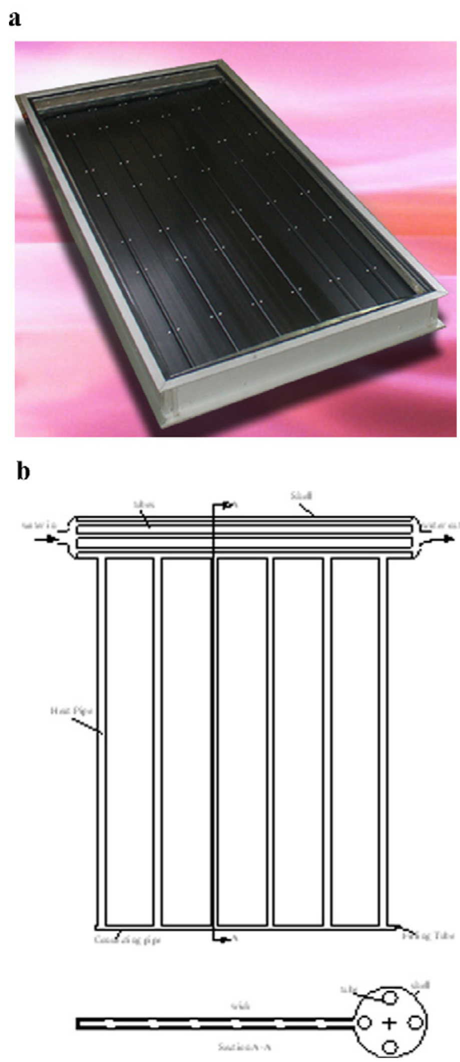

Fig. 4. Heat pipe solar collector Type III. (a) Constructed heat pipe solar collector. (b) Detail of heat pipe solar collector.

finned tube that is commonly use in low-pressure applications such as air-conditioning industries and dry-cooling towers. The tubes are expanded in order to have a close contact with fins. One end of the tubes is connected to a header and the other end connected to a shell with three tube passes. All three absorbers anodized matt black to enhance its ability to absorb heat. The heat absorbed by the heat pipes was removed and measured using a water-cooled heat exchanger. The absorber plates and heat exchanger were housed in an aluminium framework with a 0.5 mm thick aluminium sheet bottom. The panel rested on a backing insulation layer of 50 mm thick glass wool while the condenser section was insulated with Aeroflex sheet insulation. Ordinary glass window was chosen as the upper glazing for the collector. The air gap between the glass cover and the absorber plate was 40 mm. The glass was secured to the top of the frame by rubber gasket and aluminium angles, which permitted thermal expansion but prevented the entrance of dust and rain.

The technical specifications of collectors are given in Table 1.

4. Test procedures

Solar collectors are the key element of active solar-heating systems. They gather the solar energy, transform its radiation into heat, and then transfer that heat to a fluid flowing in the collector.

The thermal performance of the solar collector is determined by obtaining values of instantaneous efficiency for a combination of values of incident radiation, ambient temperature, and inlet fluid temperature, the difference in fluid temperature between the inlet and outlet, and mass flow rate of the heat transfer fluid.

The performance of a solar collector under steady-state conditions can be written as [15–18].

$$\frac{Q_u}{A_a} = G.F_R(\tau\alpha)_e - F_R U_L (t_{f,i} - t_a) \tag{1}$$

$$\frac{Q_u}{A_a} = \frac{\dot{m}}{A_a} C_p (t_{f,e} - t_{f,i}) \tag{2}$$

The solar collector efficiency is defined as

$$\eta = \left(\frac{A_a}{A_g}\right) F_R[(\tau\alpha)_e - U_L \frac{(t_{f,i} - t_a)}{G} \tag{3}$$

The instantaneous efficiency of a solar collector is generally defined as the ratio of the average useful power gained from the collector to the average solar irradiance incident at the collector aperture area.

Eq. (3) indicates that if the efficiency, η is plotted against $(t_{f,i} - t_a)/G$, a straight line will result provided U_L is constant. The slope is equal to $(A_a/A_g)F_R[(\tau\alpha)_e U_L$ and the y intercept is equal to $(A_a/A_g)F_R[(\tau\alpha)_e$.

Fig. 5. Heat pipe filling rig.

The maximum efficiency which can be reached (i.e. efficiency when the mean fluid temperature is equal to the ambient temperature).

5. Experimental setup and procedure

The experimental investigation was conducted to measure the thermal efficiency of three solar collectors. A closed loop configuration was employed for testing the collectors as shown in Fig. 6. The solar collectors were installed and tested under outdoor field conditions in Tehran (latitude 35.7°N; longitude 52.3°E altitude 1190 m). The collectors were mounted on the stand, oriented N–S, tilted 35.7°N towards the south and tested in outdoor conditions. The collectors' efficiencies were determined according to the procedure proposed by ASHRAE standard 93-1986 [17].

The hydraulic loop is divided in three lines: the first one goes to the finned tube flat plate collectors (Type I), the second one goes to the collector with double pipe condenser (Type II) and the third one goes to collector with shell and tube condenser. One pump is used to circulate the liquid.

Thermocouples were used to measure the water temperature at the inlet and outlet of the condenser. One thermocouple measuring outdoor temperature was placed in a shaded position immediately in the back of the collector. All thermocouples were made of nickel chromel/nickel aluminium (Cr/Al) wire. All temperatures were recorded on a multi-point chart recorder. Solar radiation was measured by means of a Kipp & Zonnen CM5 pyranometer, classified as secondary standard by the World Meteorological Organization (WMO), measures the global short wave radiation from both the sun and the sky on the plane of the collectors. Pyranometer, connected to a pen recorder to measure the radiation continuously during the test.

Physical quantities measured are: cooling water temperatures at the inlet and outlet of the collectors, ambient temperature, circulating water flow rate, and the incident solar irradiance on the plane of the solar collector. The global radiation was measured with pyranometer which was installed such that its aperture was levelled with the aperture of the collector without casting shadow on the collector. The irradiation was continuously recorded along with the rest of the data streams. The ambient temperature sensor was located behind the collector and shielded from direct irradiance. The temperatures were measured with chromel–alumel thermocouples (Type K), whose signals were recorded.

The experiment was carried out at a different water inlet preheated to the desired temperature as it passed through an electric heater in a tank controlled by a variable-output AC voltage-transformer. The circulating fluid flow rate was regulated by means of a needle valve and was measured with a flow meter. The fluid was circulated by a centrifugal pump. The water passed through the circulating pump, the collector, and the storage tank in order to exchange the heat with the water inside the tank. The water flow rate was almost constant in the range of 0.03–0.032 kg/s for each collector.

6. Results and discussion

The collector efficiency was calculated by measuring the heat rise between the inlet and the outlet and the insolation multiplied by the transparent frontal area of the collector. This was then plotted against temperature of the heat transfer fluid entering the collector minus the ambient air temperature divided by the global solar irradiance upon the aperture plane of the collector value. This enables the initial efficiency and the slope of the efficiency line to be calculated. The result of the three types of heat pipe solar collector is shown in Fig. 7.

The figure shows the instantaneous thermal efficiency of a solar collector is defined as the amount of energy removed by the transfer fluid per unit of frontal area during the specified time period divided by the total solar radiation incident on the collector per unit area during the same test period, under the steady-state condition.

Fig. 7 shows an intersection between the efficiency curves for the collector Types I–III at reduced temperature parameters of 0.038. This proves that good design of Type II and III collectors have an obvious enhancement over that for the collector Type I in the practical range of reduced temperature parameter.

Comparison between the three Types I–III reveals that Type I produces better efficiency over all the reduced temperature parameter range. This is because of the finned absorber plate behaving as honeycomb.

The advantages of Types I and III are:

- *Ease of production*: In conventional heat pipe solar collector each heat pipe must be vacuumed, filled with working fluid, and tested individually. However, for the present design all of the construction steps happen simultaneously.

Table 1
Solar collector's specification.

Type	Condenser	Length/m	Width/m	Evaporator length/m	Condenser length or dia./m	Absorber	HP dia./m
I	Shell and tube	1.90	1.00	1.70	0.054 dia.	Extruded aluminium	0.0127
II	Double-pipe	1.85	1.00	1.55	0.300	Extruded aluminium	0.0127
III	Shell and tube	1.80	1.00	1.70	0.054 dia.	Finned tube/315fins/m	0.0127

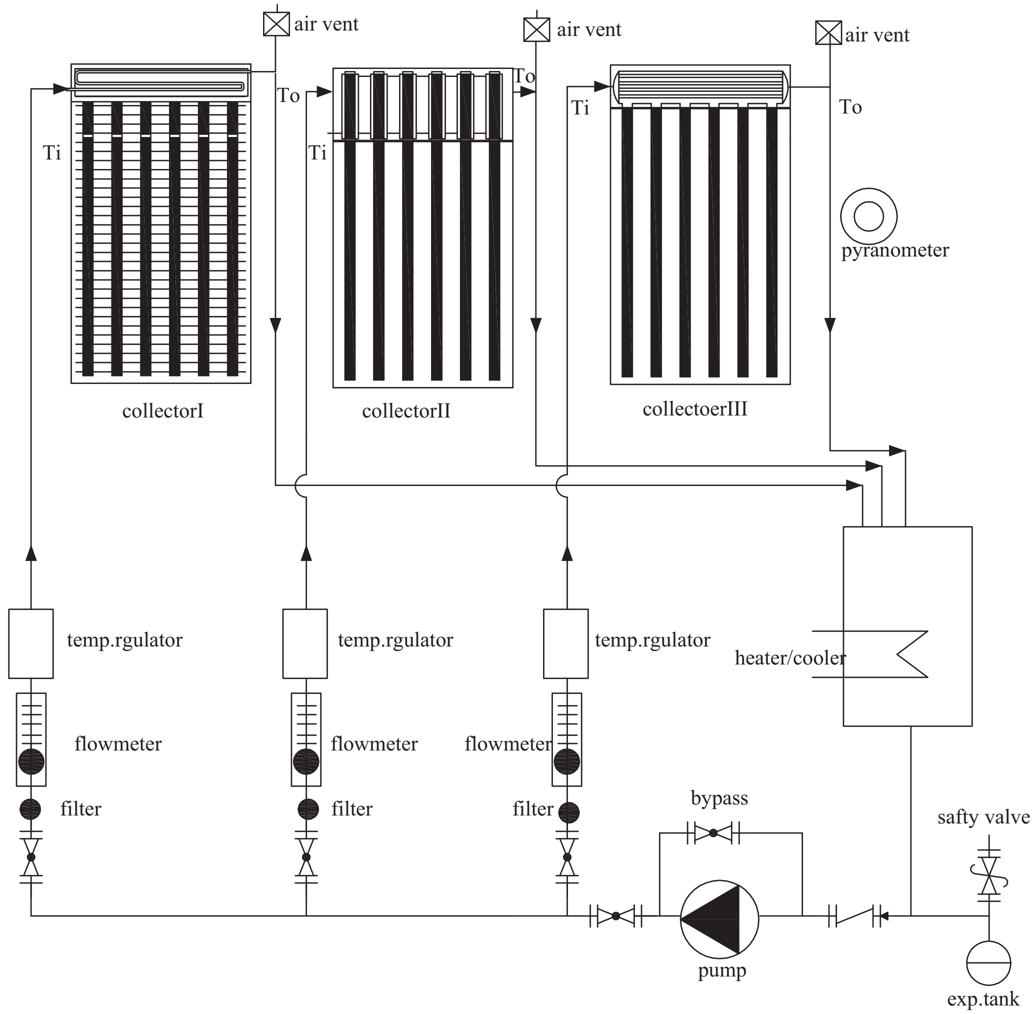

Fig. 6. Closed-loop testing configuration for solar collector.

- *Lower production cost*: Production cost would be reduced by using an interconnected heat-pipe, since all pipes can be vacuumed, filled, sealed, and tested at once.

The weakness of solar collectors “Types I and III” is that leakage in one heat pipe causes the collector ceases to operate.

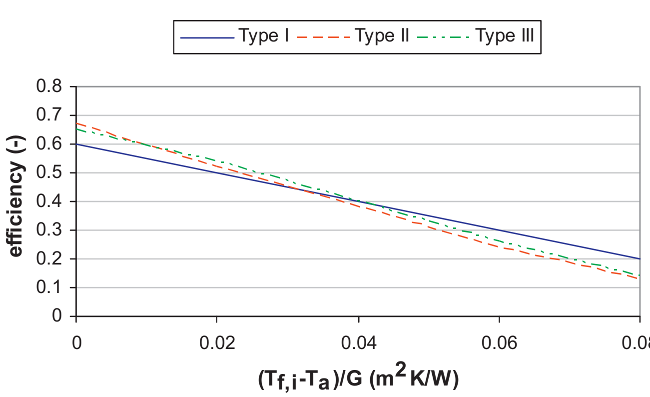

Fig. 7. Heat pipe solar collectors’ efficiency line.

7. Conclusion

The performance of three types of heat pipe solar collector were tested and plotted. The performance all three types are satisfactory with their own advantages and disadvantages.

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